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SIMULATION OF HEAT TRANSFER TO KAOLIN SLURRY WHICH EXHIBITS ENHANCED DAMPING OF TURBULENCE

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ABSTRACT

The paper deals with simulation of mass and heat transfer of Kaolin slurry with a yield stress. The yield stress is caused mainly by very fine solid particles which are of non-settling type. Slurries with the yield stress appear frequently in chemical engineering, biotechnology, medicine, power and paper plants, food and mining industries and are often strongly influenced by heat exchange between the transported materials and the surroundings.

The paper is focused on heat transfer in hydro-dynamically and thermally developed turbulent pipe flow of Kaolin slurry. The slurry contains solid particles with averaged diameter about 5 μm, and concentration of solid phase which varies from 0% to 40% by volume. Experiments proved that such slurries exhibit enhanced damping of turbulence, so they require especially designed wall damping function. Simulation of slurry assumes that it is a single-phase flow with increased viscosity and density, and rheological properties can be described by Bingham model. The wall temperature and heat flux applied into the pipe wall are steady.

The objective of the paper is to examine the influence of solids volume fraction on heat transfer by taking into account momentum and energy equations, and turbulence model with modified turbulence damping function. The effect of influential factors on the heat transfer between the pipe and the slurry were analyzed. The paper demonstrates substantial influence of solids volume fraction on velocity profile and as a consequence the temperature profile too. The results of numerical simulation demonstrate the importance of turbulence damping near a pipe wall. A possible cause of turbulence damping in the near-wall region is discussed.

NOMENCLATURE

C_i	[-]	Constant in Launder and Sharma turbulence model, i=1, 2
C_V	[%]	Solids concentration (cross sectional solids volume fraction)
c_P	[J/(kg K)]	Specific heat at constant pressure
d_P	[μm]	Solid particle diameter
D	[m]	Inner pipe diameter
f_μ	[-]	Turbulence damping function at the pipe wall
k	[m^2/s^2]	Kinetic energy of turbulence
Nu	[-]	Nusselt number
Pr	[-]	Prandtl number
p	[Pa]	Static pressure
q	[W/m]	Input power of heat per unit pipe length
r	[m]	Distance from symmetry axis
R	[m]	Inner pipe radius
Re	[-]	Reynolds number
t_μ	[s]	Relaxation / response time of solid particle in liquid velocity
t_T	[s]	Relaxation / response time of solid particle in liquid temperature
T	[K]	Temperature
U	[m/s]	Velocity component in ox direction
V	[m/s]	Velocity component in or direction
u’, v’	[m/s]	Fluctuating components of velocity U and V
x	[m]	Coordinate for ox direction
y	[m]	Coordinate for oy direction or distance from the pipe wall
$\overline{\ }$	[-]	Time averaged

Special characters

α	[W/(m^2 K)]	Heat transfer coefficient (convective heat transfer)
λ	[W/(m K)]	Thermal conductivity of water or slurry
ε	[m^2/s^3]	Rate of dissipation of kinetic energy of turbulence
μ_L	[Pa·s]	Dynamic viscosity of water
μ_t	[Pa·s]	Turbulent viscosity of water or slurry flow
μ_{ap}	[Pa·s]	Apparent viscosity of slurry
μ_{PL}	[Pa·s]	Plastic viscosity in Bingham rheological model
ν	[m^2/s]	Kinematic viscosity coefficient of water or slurry
ρ	[kg/m^3]	Density of water or slurry
σ_i	[-]	Diffusion coefficients in k–ε turbulence model, i = k, ε
τ	[Pa]	Shear stress
τ_o	[Pa]	Yield shear stress
τ_w	[Pa]	Wall shear stress
Φ	[–]	General dependent variable, $\Phi = \rho, c_p, \lambda$,

Subscripts

ap	Apparent
b	Bulk (cross sectional averaged value)
i	Index, i = 1, 2
t	Turbulent
w	Solid wall

INTRODUCTION

Solid-liquid flows appear frequently in chemical engineering, biotechnology, medicine, power and paper plants, food and mining industries. Transport of solids in pipes by using liquid as a carrier phase has low operating and maintenance costs and therefore it is still the preferred method [1].

It is common that solid-liquid mixtures are often considered as non-Newtonian and therefore require a proper rheological model. Solid-liquid mixtures can exhibit a yield stress, which is mainly caused by presence of very fine solid particles. Such slurries with very fine solid particles are of non-settling type. Nguyen and Boger [2] suppose that the yield stress is linked to the interaction and attraction among particles, giving rise to structures larger than the primary crystals, known as flocks. The yield stress then represents the breaking limit of these structures.

Slurries can be recognised as settling or non-settling types. Doron and Barnea [3] identified the flow patterns of slurries flowing in horizontal pipes as the velocity decreases:

- fully-suspended flow, in which all the particles are suspended;
- flow with a moving or stationary bed, in which the particles accumulate at the pipe bottom and form a packed bed either sliding or fixed.

Settling slurries are formed mainly by coarse particles. Settling slurries could also exist for medium and fine solid particles if solids density is high and bulk velocity is sufficiently low. When predicting frictional head loss for slurry flow with coarse or medium solid particles, it is reasonable to assume Newtonian model, as now one can measure rheology in such slurries, [4].

Non–settling slurries contain very fine solid particles and the particles can follow the motion of the fluid so that turbulent diffusion produces a uniform concentration distribution within the pipe. Such slurries can form stable homogeneous mixture, which exhibits increased density and apparent viscosity. Wilson and Thomas [5] reported that slurries with very fine solid particles exhibit thicker viscous sublayer, resulting from increased damping of turbulence in the near-wall region. The starting point in building a set of equations for such slurry flow is Navier-Stokes equation. As such slurry usually posses the yield stress, an adequate rheological model and its apparent viscosity is required in order to predict its movement. Navier-Stokes equations can be solved analytically, which is usually complicated, or numerically. If numerical methods are considered we can use at least one of the following approaches: Direct Numerical Simulation (DNS), Modelling of Turbulence (RANS) or Large Eddy Simulation (LES). In the present paper the Random Averaged Navier-Stokes equations are used. In such a case the turbulent stress tensor appears in the momentum equation, which requires an additional equation or equations in order to close the equations set. The components of the turbulent stress tensor can be calculated directly or indirectly. If the indirect method is employed, as in the presented paper, we can apply Boussinesque hypothesis, which uses the turbulent viscosity. The turbulent viscosity can be calculated using any turbulence model. If turbulence model is employed in order to calculate the turbulent viscosity, and then the turbulent stress tensor, a properly defined wall damping function is needed.

Measurements of slurry flow with high concentration of solids are avoided because of the risk of damage or contamination of intrusive hot-film or hot wire probes. Also, experiments are more complicated in the vicinity of a solid wall. With optical methods, attenuation of the beams by particles occurs. As a result of these difficulties, at concentration of solids above 25% by volume, most of the measurements in the literature concern dilute suspensions or gas-liquid, or gas-solid flows. Other non intrusive methods, including ultrasonic or magnetic ones, are more suitable for qualitative than quantitative results, as resolution is still not satisfied.

In the absence of reliable turbulence measurements related to the immediate vicinity of a pipe wall over a wide range of solids volume fraction, it is difficult to suggest a new turbulence models to describe a slurry flow with heat transfer. However, it is possible to modify the existing turbulence models in order to predict frictional head loss, velocity and temperature distributions. Such turbulence model can be developed basing on standard turbulence model by comparing calculated and measured global parameters, which are particularly relevant in engineering applications. Of course this requires additional assumptions and a proper wall damping function and rheological model too.

The paper deals with turbulent Kaolin slurry flow, which contains fine solid particles with averaged diameter about d_p=5 μm, and concentration of solid phase changing from 0% to 40% by volume. The flow is hydro-dynamically and thermally fully developed and takes place in a straight horizontal pipeline. The slurry is treated as a single-phase flow with apparent viscosity and increased density, and exhibits enhanced damping of turbulence. The mathematical model of slurry flow constitutes a conservation form of momentum and energy equations. As such slurry exhibits a yield stress the Bingham rheological model was chosen in order to calculate the slurry apparent viscosity. The problem of closure of constitute equations is solved by two-equation turbulence model in which turbulence damping function was properly designed for slurry with increased turbulence damping. In addition, a convective term, which exists in the energy equation, was determined from the energy balance acting on a unit pipe length, assuming that the temperature in the main flow direction varies linearly. Finally, the mathematical model of non-isothermal turbulent Bingham slurry flow comprises four partial differential equations solved by fine-difference scheme. The mathematical model allows for predicting frictional head loss, and velocity, and temperature distribution in Kaolin slurry flow. The mathematical model was validated previously for isothermal flow. The mathematical model was not validated for heat exchange as there are no desired experimental data. The only validation performed for heat exchange concern carrier liquid flow.

The objective of the paper is the qualitative examination of the solids volume fraction influence on heat transfer in Kaolin slurry flow by taking into account the mathematical model with especially designed turbulence damping function.

LITERATURE REVIEW

In the case of solid-liquid flow the number of models is very limited, however, someone can mention the one-equation turbulence model of Danon et al. [6], Mishra et al. [7] or two-equation model of Yulin [8] and Ling et al. [9]. Danon et al. [6] built one-equation 'k-l' turbulence model using an empirical turbulence length scale. Two-equation k-ε-Ap turbulence model of Yulin [8] is built using kinetic energy of turbulence and its dissipation rate the same as in the standard turbulence model for a single-phase flow. The 'Ap' is an algebraic equation describing the solid phase. These mathematical models have been successfully examined, however, only for low solids concentration.

Transport of fine solid particles is often strongly influenced by heat exchange between the transported materials and the surroundings. Researchers are developing methods and techniques to enhance or attenuate the heat transfer process. Heat transfer enhancement contributes to energy saving and preservation of the environment. Those methods are recognised as active, passive, destabilization, multiphase and control methods [10]. The passive ones like inserted wire coils or mechanically deformed pipes, have been studied for the last several years, and have become commercial solutions. The active techniques can produce very high increases in heat transfer [11].

Particles in solid-liquid flow might enhance or suppress the rate of heat transfer, which depends on the level of turbulence. The level of turbulence depends on particle size, solids volume fraction, solid and liquid phase properties, and flow condition. The heat transfer characteristics in turbulent flow of solid-liquid suspension of Kaolin are not well understood due to the complexity of interactions between solid particles and carrier liquid. Analysing literature on prediction of heat transfer in solid-liquid turbulent flow with fine solid particles it can be seen that the majority of researchers are oriented on slurries with low or moderate concentration of solid particles, while slurries with high solids volume fraction, which are presented in the paper, are scattered. As there are several limitations in experiments due to behaviour of solid particles in the vicinity of a pipe wall, especially if volume fraction of solids is high, we still face limitation in access to measurements, and as a consequence, to proper prediction of frictional head loss, velocity, and temperature distributions.

Influence of solid particles submerged in carrier liquid on heat transfer in turbulent flow has been experimentally investigated be several researches [12-18]. Wang et al. [18] examined experimentally thermal conductivity of nano-particles of Al_2O_3 and CuO mixed with water, vacuum pump liquid, engine oil, and ethylene glycol. The averaged particle diameter of the Al_2O_3 was 28 nm, and the averaged particle diameter of the CuO was 23 nm. All particles were loosely agglomerated in chosen liquids. Experiments proved that the thermal conductivity of the mixture increases with the volume fraction of the Al_2O_3 particles. Increase of the mixture thermal conductivity depends on liquid and solid phase properties. They proved that increase of the mixture thermal conductivity in ethylene glycol and engine oil are the highest, whereas that in the pump liquid is the lowest. The effective thermal conductivity of ethylene glycol increases by 40% when solids concentration of Al_2O_3 was 8% by volume.

Rozenblit et al. [19] made an experimental study on heat transfer coefficient associated with solid-liquid mixture transport in horizontal pipe using electro-resistance sensor and infra-red imaging. They considered flow of acetal-water mixture with moving bed for solids volume fraction from 5% to 15% by volume. The experimental results included the temperature distribution on the heated wall and the vertical solids volume fraction distribution. They learned that the local heat transfer coefficient changes from its lowest value at the bottom of the pipe, to highest values above carrier liquid at the upper heterogeneous layer. It clearly means that the heat transfer coefficient is strongly influenced by the cross sectional distribution of the solid phase in the pipe. In order to analyse the near wall structures they used algebraic three layer model of Doron and Barnea [20] suitable to predict pressure drop and the solids volume fraction distribution across the pipe.

The heat exchange in slurry flow depends on several parameters including solids volume fraction, carrier liquid and solid phase properties, flow rate, flow geometry and boundary conditions. When solid particles are sufficiently small, the relaxation time (t_μ), which indicates how fast a particle can respond to a change in flow velocity, and the thermal response time (t_T), which indicates how fast a particle can respond to changes in liquid temperature, defined by equation (1) and equation (2), respectively, are low and the particle can respond fast on changes in carrier liquid and temperature fluctuations. In such a case turbulent diffusion produces uniform distribution of solids volume fraction across the pipe. Thus such fine particles are of non-settling type and the flow can be treated as a single phase flow with increased viscosity and density.

$$\mathbf{t_\mu = \frac{d_P^2\,\rho_P}{18\mu_L}} \tag{1}$$

$$\mathbf{t_T = \frac{c_P\,d_P^2\,\rho_P}{12\lambda_L}} \tag{2}$$

Analysing literature on prediction of solid-liquid flow it can be seen that main focus is oriented on solid-liquid interactions and heat exchange process has secondary meaning. Besides, researchers are mainly oriented on slurries with low solids volume fraction (dilute solutions) while slurries with moderate and high solids volume fraction are most interesting for engineering applications. As there are many limitations in experiments on behaviour of solid particles in the vicinity of the pipe wall, especially if solids volume fraction is high, we still face limitations in exact prediction of pressure drop and velocity distribution. This is even more pronounced if the heat exchange is taking into account.

PHYSICAL AND MATHEMATICAL MODEL

The physical model assumes fully-suspended flow of Kaolin slurry (d_P=5μm) which exhibits a yield stress. The slurry is non-settling, homogeneous and consists of very fine solid particles with density of about 2400 kg/m^3. The carrier liquid is water. The solids concentration varies from C_V=0% to C_V=40% by volume. It is assumed that slurry viscosity is described by apparent viscosity and is assigned by the Bingham rheological model. The apparent viscosity and the slurry density are constant across the pipe for isothermal flow and dependent on temperature for non-isothermal flow. The flow in horizontal pipe is hydro-dynamically and thermally fully developed and turbulent. The flow is axially symmetrical and without circumferential swirls. Heat resistance of the pipe wall is neglected. Steady heat flux acting on unit pipe length is applied and temperature of pipe surface is constant. Slurry temperature in **ox** direction is changing in linear way.

Taking into account the aforementioned physical model, the continuity equation and the time-averaged momentum equation, in cylindrical co-ordinates, in which **ox,** as symmetry axis of a pipeline, is a main flow direction, and **or** is radial direction, can be described as follows:

$$\frac{\partial}{\partial x}(\bar{\rho}\bar{U}) + \frac{1}{r}\frac{\partial}{\partial r}(r\bar{\rho}\bar{V}) = 0 \qquad (3)$$

$$\frac{1}{r}\frac{\partial}{\partial r}\left[r\left(\mu_{ap}\frac{\partial\bar{U}}{\partial r} - \bar{\rho}\overline{u'v'}\right)\right] = 0 \qquad (4)$$

In continuity equation (3), the time averaged velocity component in **or** direction is zero (**V**=0), as the flow is axially symmetrical, and the term ∂U/∂x=0, as the flow is hydro-dynamically fully developed. Assuming that ∂ρ/∂x≈0, which simplify mathematical model, we can write that U(∂ρ/∂x) =0. Concluding one can say that both components at the left hand side of equation (3) are zero.

Apparent viscosity, which exists in equation (4), was calculated using Bingham rheological model, as the model is adequate for such slurry. Taking into account Bingham and Newtonian model of Kaolin slurry one can write [21]:

$$\mu_{ap} = \frac{\mu_{PL}}{\left(1 - \frac{\tau_o}{\tau_w}\right)} \qquad (5)$$

while the wall shear stress, which appeared in equation (5), is designated from balance of forces acting on unit pipe length, so the wall shear stress can be calculated as follows:

$$\tau_w = \frac{dp}{dx}\frac{D}{4} \qquad (6)$$

The turbulent stress component, which appeared in equation (4), is designated by the Boussinesque hypothesis, as follows:

$$-\rho\overline{u'v'} = \mu_t\frac{\partial\bar{U}}{\partial r} \qquad (7)$$

The turbulent viscosity (μ_t), stated in equation (7), was designated by Launder and Sharma turbulence model [22], with the support of dimensionless analysis, as follows:

$$\mu_t = f_\mu\frac{\bar{\rho}k^2}{\varepsilon} \qquad (8)$$

The kinetic energy of turbulence (k) and its dissipation rate (ε), which appeared in equation (8), are delivered from Navier-Stokes equations. Earlier research proved that Launder and Sharma turbulence model has a potential to predict slurry flows [23], therefore this turbulence model was chosen in the research. The final forms of k and ε equations, for the aforementioned assumptions, are the same as in the standard turbulence model of Launder and Sharma [22], and are the following:

- equation for kinetic energy of turbulence:

$$\frac{1}{r}\left[r\left(\mu_{ap} + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial r}\right] + \mu_t\left(\frac{\partial\bar{U}}{\partial r}\right)^2 = \bar{\rho}\varepsilon + 2\mu_{ap}\left(\frac{\partial k^{1/2}}{\partial r}\right)^2 \qquad (9)$$

- equation for dissipation rate of kinetic energy of turbulence:

$$\frac{1}{r}\left[r\left(\mu_{ap} + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial\varepsilon}{\partial r}\right] + C_1\frac{\varepsilon}{k}\mu_t\left(\frac{\partial\bar{U}}{\partial r}\right)^2 = C_2\left[1 - 0.3\exp\left(-\mathrm{Re}_t^2\right)\right]\frac{\bar{\rho}\varepsilon^2}{k} - 2\frac{\mu_{ap}}{\bar{\rho}}\mu_t\left(\frac{\partial^2\bar{U}}{\partial r^2}\right)^2 \qquad (10)$$

The turbulent Reynolds number, which appeared in equation (10), was defined by Launder and Sharma [22], however, instead of dynamic viscosity the apparent viscosity is used, which equation (11) describes.

$$\mathrm{Re}_t = \frac{\bar{\rho}k^2}{\mu_{ap}\varepsilon} \qquad (11)$$

The crucial point of the mathematical model is proper determination of turbulence damping function (f_μ), which appeared in equation (8). Wilson and Thomas [5] concluded that in fine-dispersive slurry flow a region close to the pipe wall exhibits increased viscous sub-layer. Therefore the turbulence damping function (f_μ), which is an empirical function, was redesigned in order to predict enhanced damping of turbulence in the near-wall region. The new turbulence damping function includes dimensionless yield stress, and is determined by the following empirical equation [24]:

$$f_\mu = 0{,}09\exp\left[\frac{-3{,}4\left(1 + \frac{\tau_o}{\tau_w}\right)}{\left(1 + \frac{\mathrm{Re}_t}{50}\right)^2}\right] \qquad (12)$$

The standard turbulence damping function at the pipe wall (f_μ), proposed originally by Launder and Sharma [22], is the following:

$$\mathbf{f_\mu = 0,09\exp\left[\frac{-3,4}{\left(1+\frac{Re_t}{50}\right)^2}\right]} \qquad (13)$$

It is seen that the new turbulence damping function, determined by (12), compared to the standard damping function (13), demonstrates enhanced turbulence damping. If the yield stress goes to zero the new turbulence damping function goes to the standard function proposed by Launder and Sharma [22] for Newtonian fluids. The new turbulence damping function (12) has been set up by taking into account experimental data of global parameters for a comprehensive range of rheological parameters and flow conditions [21, 25].

Finally, the mathematical model for isothermal Kaolin slurry flow comprises three partial differential equations, namely (4), (9) and (10), together with complimentary equations (5) - (8), (11) and (12).

In order to study the influence of solids volume fraction on heat transfer exchange in the slurry flow, the mathematical model is extended by taking into account the following energy equation written for temperature:

$$\mathbf{\bar{\rho}\bar{U}\frac{\partial\bar{T}}{\partial x} = \frac{1}{r}\frac{\partial}{\partial r}\left[r\left(\frac{\mu_{ap}}{Pr}+\frac{\mu_t}{Pr_t}\right)\frac{\partial\bar{T}}{\partial r}\right]} \qquad (14)$$

while the Prandtl number is calculated for Kaolin slurry, using apparent viscosity, as follows:

$$\mathbf{Pr = \frac{\mu_{ap}c_P}{\lambda}} \qquad (15)$$

The turbulent Prandtl number, which appeared in equation (14), was intensively examined by several researchers. Their studies indicated that for the flow on the plate, the turbulent Prandtl number is about Pr_t=0.5, while for the boundary layer is about Pr_t=0.9 [26].

Convective term in equation (14), which includes changes of slurry temperature along the flow direction, was calculated on the basis of the energy balance equation. Taking into account the heat flux acting on the unit pipe length (Δx=1m) in thermally fully developed slurry flow, and assuming that temperature in **ox** direction varies linearly, the final form of the convective term in equation (14), can be set up following:

$$\mathbf{\frac{\partial\bar{T}}{\partial x} = \frac{2q}{\bar{\rho}_b\bar{U}_b(c_p)_b R^2}} \qquad (16)$$

Slurry properties, like density (ρ), specific heat (c_p) and thermal conductivity (λ) are dependent on temperature and volume fraction of solids. Taking into account general variable $\Phi = \rho, c_p, \lambda$, these properties were calculated as follows:

$$\mathbf{\Phi = \Phi\,(1-C_V) + \Phi\,C_V} \qquad (17)$$

Finally, for non-isothermal slurry flow, the mathematical model comprises four partial differential equations, namely momentum and energy equations, and equations for kinetic energy of turbulence and its dissipation rate. Partial differential equations, namely (4), (9), (10) and (14), together with complimentary equations (5)-(8), (11), (12), (15), (16), and (17) were solved by finite difference scheme using own computer code. The mathematical model is suitable to predict velocity distribution, frictional head loss, and temperature distribution of fine-dispersive slurry with a yield stress in a straight pipeline.

NUMERICAL METHOD

Numerical computations were performed for known dp/dx. Constants in the turbulence model are the same as those in the turbulence model of Launder and Sharma [22] and equal: C_1=1.44; C_2=1.92; σ_k=1.0; σ_ε=1.3, Pr_t=0.9. The mathematical model assumes non slip velocity at the pipe wall, i.e. U=0, and k=0, ε=0. Axially symmetrical conditions were applied at the pipe centre, therefore: dU/dr=0, dT/dr=0, dk/dr=0 and dε/dr=0.

After determining boundary and convergence conditions the mathematical model was solved by finite difference scheme. A differential grid of 80 nodal points distributed on the radius of the pipe was used. The majority of the nodal points were localized in a close vicinity of a pipe wall to ensure the convergence process. The number of nodal points was set up experimentally to ensure nodally independent computations.

VALIDATION OF THE NUMERICAL MODEL

The mathematical model for isothermal flow of Kaolin slurry, which includes especially designed turbulence damping function, described by equation (12), was successfully validated for fully developed turbulent pipe flow in a broad range of yield stresses, plastic viscosity and pipe diameters, [21, 25, 27-29].

$$\mathbf{Nu = 0.023 * Re^{0.8}\,Pr^{1/3}} \qquad (18)$$

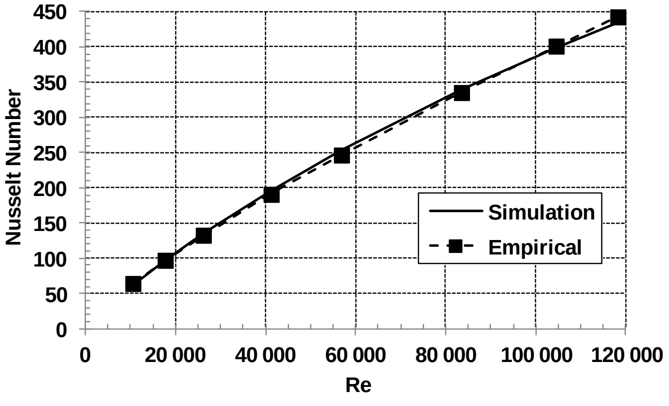

Figure 1 Comparison of numerically and empirically predicted Nusselt number for carrier liquid flow, q=200 W/m, D=0.012 m, T_w=308.15 K.

Due to the lack of experimental data of thermal properties for such slurry flow, the mathematical model for non-isothermal flow was validated for thermally fully developed turbulent flow of carrier liquid only. Results of numerical prediction of Nusselt number for carrier liquid flow are compared with calculations using empirical formula, described by equation (18), and are presented in Figure 1. The minimum Reynolds number used in calculations was Re=10,500 and the maximum was Re=118,200. The reason why maximum Reynolds number is not so high is that in a case of slurry flow the Reynolds number is not so high, as ratio of momentum forces to viscous forces is not high either. Relative error of predicted Nusselt number, compared with empirical formula, varies from -3% to +3% in the demonstrated range of Reynolds number, which Figure 1 presents. Possible reason for such discrepancy could be caused by assumptions made in convective term (16). It is seen in equation (16) that liquid properties are constant and equal to bulk values, which is not quite right.

SIMULATION RESULTS

As mentioned above the crucial point in the mathematical model is the turbulence damping function. In order to illustrate the importance of turbulence damping function, Figure 2 shows the standard wall damping function (solid line), proposed by Launder and Sharma [22], and especially developed wall damping function, called the new wall damping function, described by equation (12), for two arbitrary chosen dimensional yield stresses, i.e. τ_o/τ_w = 0.25 and τ_o/τ_w = 0.50 (dashed lines with points) [21]. The turbulent Reynolds number is defined by equation (11). It is seen in Figure 2 that for turbulent Reynolds number, in the range from 0 to 100, the new wall damping function gives lower values, compared to the standard one, while for Re_t>100 the difference between both wall damping functions almost does not exists. This means that the new wall damping function causes increased damping of turbulence in a close vicinity of a solid wall. The lower value of the new turbulence damping function at the pipe wall causes decrease of turbulent stress tensor. Decrease of turbulent stress tensor means that enhanced turbulence damping appears.

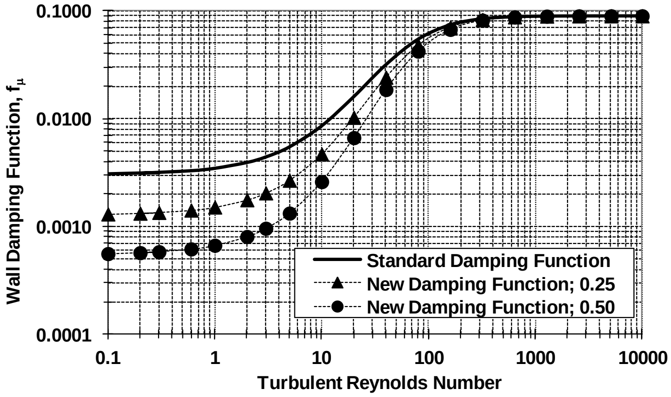

Figure 2 Importance of turbulence damping function near a pipe wall.

Numerical simulations of non-isothermal turbulent flow of Kaolin slurry were made for two sets of measurements of real Kaolin slurry. Density and rheological properties of such slurry was calculated using Bingham model and are stated in Table 1.

Table 1 Rheological properties of Kaolin slurries.

C_V %	ρ kg/m^3	ρ_S kg/m^3	τ_o Pa	μ_{PL} Pa s
0.0%	998.2	0	0.00	1.002 10^{-3}
7.4%	1105.3	2440	4. 92	4.330 10^{-3}
38.3%	1535.0	2400	9.00	1.300 10^{-2}

For slurries, stated in Table 1, the relaxation time of solid particles in liquid velocity is almost identical for both solids volume fractions (C_V=7.4% and 38.3%) and equals to t_μ= 13.53 μs, while relaxation time of solid particle in liquid temperature is equal to t_T = 120.5 μs for C_V=7.4% and t_T = 61.8 μs for C_V=38.3%.

In simulation of Kaolin slurry flow with heat exchange it is assumed that the wall temperature is constant and equal to 293.15 K. Steady heat flux acting on unit pipe length was applied and equal to q = 200 W/m. Numerical simulations were made for slurry flow in the pipe of inner diameter D=0.0127 m and for volume fraction of solids equal C_V=0%, 7.4%, and 38.3%.

$$\mathbf{Re_{ap}} = \frac{\boldsymbol{\rho_b}\,\mathbf{U_b}\,\mathbf{D}}{\boldsymbol{\mu_{ap}}} \tag{19}$$

Numerical predictions confirmed substantial influence of solids volume fraction and as a consequence the yield stress on heat exchange in Kaolin slurry flow. Figure 3 shows temperature distribution in slurry flow for C_V=(0, 7.4, 38.3)%. It is demonstrated that temperature difference $\Delta T=T_w-T_b$ arises if concentration of solids increases. If temperature difference between pipe wall and the slurry increases the heat transfer coefficient decreases because q=const. Predictions confirmed that even small changes in velocity distribution significantly affect temperature distribution, as shown by comparing Figure 3 with Figure 4. Figure 4 demonstrates influence of volume fraction of solids on velocity profile near a pipe wall. Proper defining of Reynolds number, which in the paper is based on apparent viscosity, and is defined by equation (19), is always problematic. In order to avoid such uncertainty the simulations, presented in Figure 3 and Figure 4, were made for the same bulk velocities equal U_b=3.68 m/s.

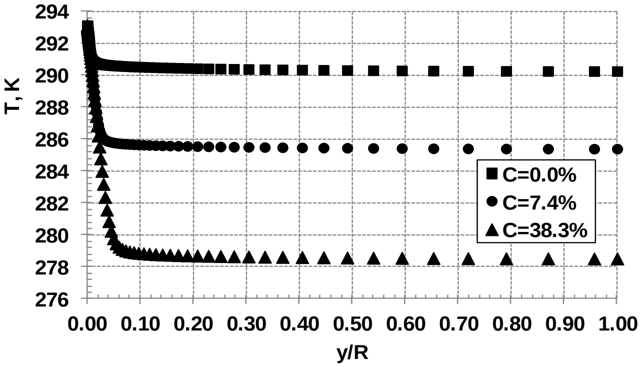

Figure 3 Temperature distributions in Water and Kaolin slurry flows at constant bulk velocities U_b=3.68 m/s, D=0.0127 m.

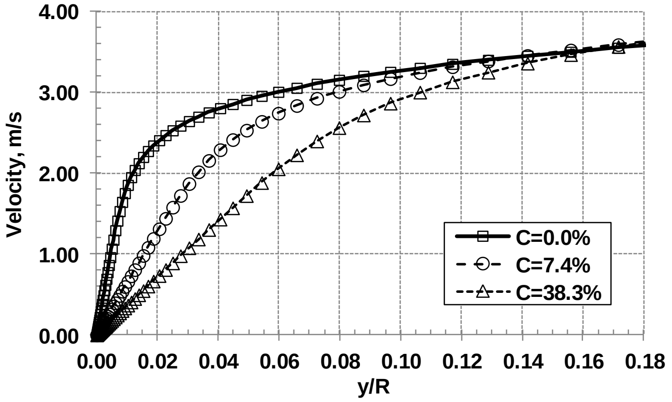

Figure 4 Velocity distributions for water and slurry flows at the pipe wall for U_b=3.68 m/s, D=0.0127 m.

$$\alpha = \frac{\mathrm{Nu}\,\lambda}{\mathrm{D}} \tag{20}$$

As already mentioned, increasing volume fraction of solid particles causes reduction of heat transfer coefficient (α), defined by equation (20). Lower heat transfer coefficient means that, for the same heat flux acting on the unit pipe length of radius R, and for the same boundary conditions, the Nusselt number decreases. This phenomenon is illustrated in Figure 5.

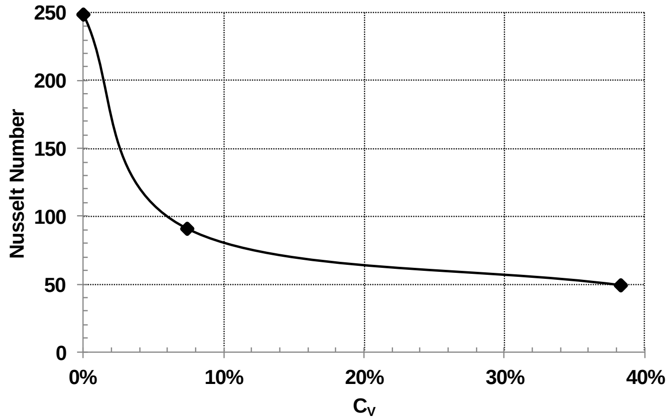

Figure 5 Dependents of solids volume fraction on Nusselt number at constant U_b=3.68 m/s and D=0.0127 m.

Heat transfer coefficient depends on many parameters, but is also influenced by the flow regime. Taking into account Reynolds number, defined by equation (19), simulation demonstrates that Nusselt number increases substantially with Reynolds number increase, which is shown in Figure 6. However, it is worth mentioning that so high Reynolds numbers, which are presented in Figure 6, are not realistic for slurry flow with fine particles because ratio of momentum forces to viscous forces are not so high. Real operating range of Reynolds number for the flow conditions defined earlier is Re = 4,000 – 15,000 and depends on volume fraction of solids. Figure 6 shows that Nusselt number for Kaolin slurry comparing to water flow increases significantly if solids volume fraction increases.

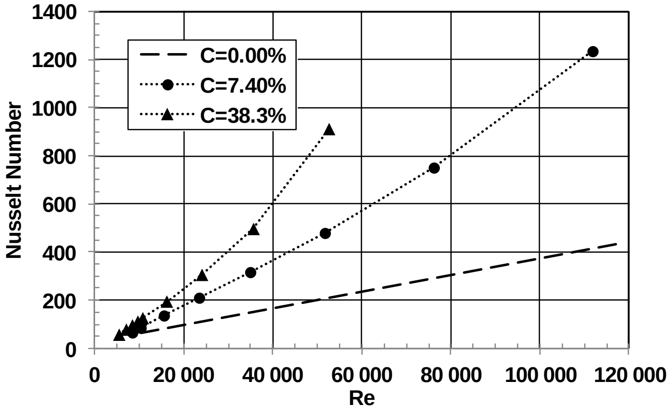

Figure 6 Dependence of Reynolds number on Nusselt number D=0.0127 m.

CONCLUSIONS

Numerical simulations of turbulent Kaolin slurry flow exhibit substantial influence of solids concentration, and/or the yield stress, on quality and quantity of heat exchange process. Predictions demonstrate substantial affect of turbulence damping function and solids volume fraction on velocity, and finally on temperature profile too.

Numerical simulation demonstrating influence of the volume fraction of solids and the Reynolds number, on the heat exchange process in turbulent flow of Kaolin slurry, allows for formulating the following conclusions:

1. CFD simulations of isothermal Kaolin slurry with support of k–ε model, which includes especially designed function of turbulence damping at the pipe wall, which has been successfully validated earlier, are of reasonable precision, so that it can be further used for the cases not supported by experiments, like the heat exchange process.
2. Solids volume fraction influence strongly on temperature distribution across the pipe and as a consequence on heat transfer process.
3. Changes of slurry velocity profiles at the pipe wall evoke significant changes in the heat transfer across the flow field.
4. If the velocity profile at the pipe wall becomes less steep, which is due to increased viscous forces, the temperature difference between a pipe wall and slurry increases. Less steep slurry velocity profile at the pipe wall results in decreased Nusselt number. As a consequence the heat transfer coefficient decreases if solids volume fraction increases.
5. The mathematical model of heat transfer in Kaolin slurry flow requires validation. This however, requires reliable data of thermal properties of such slurry flow.

Possible cause of '*damping of turbulence*", which exists in Kaolin slurry, could be due to the fact that solid particles increase the time interval of 'bursting phenomena' as particles reduce higher order fluctuations.

Another possible reason for the existence of turbulence damping could be the '*lift forces*'. As a result of lift forces larger particles are pushed away from the pipe wall and are replaced by the finer particles, enhancing the viscous forces of the slurry in the vicinity of the pipe wall. If the viscous forces are increasing the '*laminarisation*' of the flow takes place [30]. This however has limited meaning for fine particles and is more pronounced for medium and coarse particles.

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